CFD Analysis of Flow through Integral Orifice Plate Assemblies under Diverse Working Conditions

MANU B V[1], Prof. YOGESH KUMAR[2] K J and Dr. V. SESHADRI[3]

[1]M.Tech student, Department of Mechanical Engineering, Maharaja Institute of Technology, Mysore.
[2]Assistant Professor, Department of Mechanical Engineering, Maharaja Institute of Technology, Mysore.
[3]Professor (Emeritus), Department of Mechanical Engineering, Maharaja Institute of Technology, Mysore.

Abstract – The performance of characteristics of various types of integral orifice plates for diverse working conditions are analyzed using commercially available CFD software, ANSYS FLUENT.

In this present work, ANSYS FLUENT software is used for the analysis of both compressible and incompressible flow through the various types of integral orifice plates namely, square edge, conical entrance and quarter circle integral orifice plate assemblies.

The flow through the standard orifice plate is analyzed according to BS 1042 and computational results are validated with standard results.

The experimental results given by MARCELO FILARDI et al[5] and by Yokogawa electronic corporation[10] are validated by using ANSYS FLUENT and same computational methodology is used to study the variation of co-efficient of discharge (C_d) and permanent pressure loss co-efficient (C_L) with Reynolds number, diameter ratio and effect of absence of upstream and downstream pipelines.

The compressible flow through standard orifice plate is validated with CFD and same methodology is used to predict the variation of expansibility factor with Reynolds number for the various types of integral orifice plate assemblies.

***Key Words*: Co-efficient of discharge (C_d), Permanent pressure loss (C_L), CFD, ANSYS FLUENT, Integral orifice plates, Reynolds number, Expansibility factor, Diameter ratio.**

1. INTRODUCTION

Orifice meter is an obstruction type of flow meter, which is widely used for flow measurement in most of the industries like food, chemical, water supply Industries etc. BS 1042 and ISO 5167 standards provide the coefficient of discharge for certain range of diameter ratios and Reynolds numbers. But in case of specialized industrial applications the orifice meter operates at diverse conditions, that are outside the standard diameter and Reynolds number ranges.

The integral orifice meters are special type of obstruction type flow meters, which are used for small diameters and low flows. BS 1042 standard also provides the specifications for geometry and flow characteristics of integral orifice meters but there is not much research work done or information available on this type of orifice meters.

Several manufacturers like Yokogawa, Honeywell and others manufacture the integral orifice meters assemblies and they have conducted the experiments on these particular orifice meters and given the data for geometry and flow characteristic for certain range of diameters and Reynolds numbers. But there is no computational validation for experimental results and there is no further information on flow characteristics if orifice meters operate outside the specified range of Reynolds number and diameters.

Hence this research work is an attempt to simulate the flow through the integral orifice meter which operates outside the specified conditions, that is under diverse conditions.

The computational fluid dynamics (CFD) ANALYSIS FLUENT is used as a tool for modeling and analysis of integral orifice meters. Initially the simulation is carried out according BS 1042 and ISO 5167 standards and results are validated with the standards. Further the analysis is carried out for nonstandard conditions of Reynolds numbers and diameter ratio for both compressible and incompressible flows for integral orifices and studying the effects of these parameters on coefficient of discharge, permanent pressure loss coefficient and expansibility coefficient.

1.1 OPERATING PRINCIPLE OF ORIFICE METER

With an orifice plate installed in a flow stream, increases in a fluid flow velocity through the reduced area of the orifice, develop a differential pressure across the orifice. The differential pressure generated is related to the diameter ratio of the orifice plate. The smaller beta ratio causes the higher the differential pressure to be generated. In practice the choice of beta ratio is a compromise between the differential pressure desired and the flow rate required.

With the orifice plate in the pipe work, the static pressure upstream the plate increases slightly due to back pressure effect and then decreases sharply as the flow passes through the orifice. Flow downstream the orifice reaches minimum at a point called the Vena contracta where the velocity of the flow is at a maximum. Beyond Vena contracta, static pressure start to recover but it never gets to the upstream value. In other words, with an orifice meter installation, there is always a permanent pressure loss. In addition to pressure loss, some of the pressure energy is converted into sound and heat at an orifice plate.

When a fluid (whether liquid or gas) passes through the orifice, its pressure builds up slightly upstream of the orifice but as the fluid is forced to converge to pass through the hole, the velocity increases and the fluid pressure decreases. A little downstream of the orifice the flow reaches its point of maximum convergence, the vena-contracta, where the velocity reaches its maximum and the pressure reaches its minimum. Beyond that, the flow expands, the velocity falls and the pressure increases. By measuring the difference in fluid pressure across tappings upstream and downstream of the plate, the flow rate can be obtained from Bernoulli's equation

Fig1. represents the flow of fluid through orifice meter and let us consider section 1-1 at the upstream of the pipe and section 2-2 at the downstream where the pressure are to be noted . Let P_1, V_1 and A_1 are the pressure, velocity and the cross-sectional area of the pipeline at section 1-1 respectively and P_2, V_2 and A_2 are the pressure, velocity and the cross sectional area of the pipe line, at section 2-2 respectively.

The expression for theoretical flow rate is given by,

$$Q_{Theoretical} = V_2 A_2 = \frac{A_2}{\sqrt{1-\beta^4}} \sqrt{\frac{2g*(p_1-p_2)}{\rho g}}$$

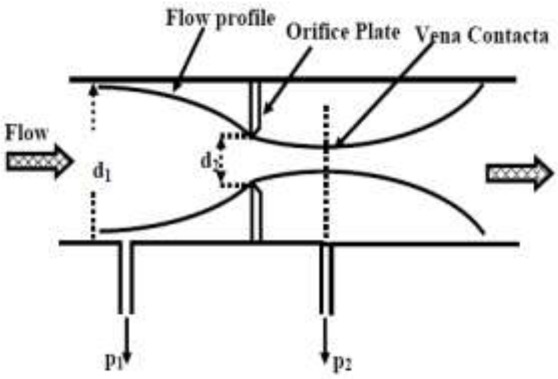

Fig1: FLOW THROUGH THE ORIFICE METER

1.2 DISCHARGE COEFFICIENT OF ORIFICE PLATE

The flow expression obtained in the above equation is not accurate in the actual case and some correction factor, such as discharge coefficient (C_d) has to be incorporated. Thus the equation becomes,

$$Q_{Actual} = C_d\, Q_{Theoritical} = C_d \frac{A_2 F_\alpha}{\sqrt{1-\beta^4}} \sqrt{2\Delta P\rho}$$

for incompressible flows.

$$Q_{Actual} = C_d\, Q_{Theoritical} = C_d \frac{A_2 F_\alpha \varepsilon}{\sqrt{1-\beta^4}} \sqrt{2\Delta P\rho_1}$$

for compressible flows.

C_d is defined as the ratio of the actual flow to the ideal flows and is always less than one.

When the orifice meter is operating at elevated temperatures, an area correction factor F_α needs to be included to account for the change in the area of the orifice hole due to thermal expansion.

When the fluid is compressible an additional factor ε the expansibility coefficient needs to be introduced which takes account of the difference between the discharge co-efficient for compressible and incompressible flows. It is given by,

$$\varepsilon = \frac{C_{dc}}{C_{di}}$$

Where

C_{dc} is discharge co-efficient for compressible flow.
C_{di} is discharge co-efficient for incompressible flow.

Calculation of C_d can be done using the formula specified in ISO-5167. The discharge coefficient is given by the Reader-Harries/Gallagher equation given by,

$$C_d = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521[10^6\beta/R_{eD}] + [0.0188 + 0.0063A]\beta^{3.5}[10^5/R_{eD}] + [0.043 + 0.080\, e^{-10L_1} - 0.123e^{-7L_1}][1 - 0.11A][\frac{\beta^4}{1-\beta^4}] - 0.031[M_2 - 0._{08M2}{}^{1.1}]\beta^{1.3}$$

If D <71.12mm (2.8 inch), the following term should be added to the equation.

$$+ 0.011[0.075 - \beta][2.8 - \frac{D}{25.4}]$$

Where D is the diameter of pipe in mm

Diameter ratio, $\beta = d/D$

R_{eD} = Pipe Reynolds number

$A = [19000\beta/R_{eD}]^{0.8}$

M_2 = Constant = $2L_2 / (1-\beta)$

L_1 and L_2 are distance from upstream and downstream depending on the type of pressure tappings used.

The above equation has its own limitations. The equation is completely empirical and is derived on the basis of extensive experimental data. It is only applicable when pipe diameter is within 50mm<D<1000mm when diameter ratio is within 0.1<β<0.75, plate thickness between 0.005D and 0.002D, bevel angle of 45°±15°.The upstream edge of the orifice hole should be sharp and a radius of curvature not greater than 0.0004d. Further the pipe surface should be smooth.

The geometry and dimensions should be as per ISO 5167 standards for the equation to be applicable. For any other non-standard cases lying outside of the mentioned range, the Reader-Harries/Gallagher Equation is invalid.

Discharge coefficient depends on Reynolds number and diameter ratio, β. But it has been observed that for $R_e>10^4$, the flow is totally turbulent and Discharge coefficient is fairly independent for Reynolds number. In this range, the typical value of Discharge coefficient for orifice plate varies between 0.6 and 0.7.

According to ISO 5167 the empirical formula for computing the expansibility [expansion] factor, ε is as follows:

$$\varepsilon=1-[0.41+0.35\beta^4]\frac{\Delta P}{KP_1}$$

This formula is applicable only within the range of the limits of,

$$\frac{P_2}{P_1}\geq 0.75$$

For orifice plates with corner tappings:

d>12.5 mm

50 mm<D<1000 mm

$0.2<\beta<0.75$

$Re_D>5000$ for $0.2<\beta<0.45$

$Re_D>10000$ for $\beta>0.45$

For orifice plates with flange tappings or with D and D/2 pressure tappings:

d>12.5 mm

50 mm<D<1000 mm

$0.2<\beta<0.75$

$Re_D>1260\beta^2 D$

Where, D is expressed in millimeters.

1.2 PERMANENT PRESSURE LOSS

Whenever the fluid flows through a pipe, the flow losses occur due to the friction between the fluid and the wall surface. The permanent pressure loss of an orifice meter is the additional loss due to the presence of orifice as an obstruction as compared to the losses in the pipe of same diameter without orifice plate. Thus the permanent pressure loss caused by the orifice meter may be determined by the pressure measurements made with the same pipe line before and after the insertion of the orifice meter as well as the pressure differential indicated by the flow meter.

If ΔP` is the difference in pressure, measured prior to the installation of the orifice plate between two pressure tappings one of which is situated far upstream of the flanges where the orifice will be inserted and the other which is far downstream of the same flanges and if ΔP`` is the difference in the pressure measured between the same pressure tappings after installation of the orifice plate between these flanges, both being measured under identical conditions of flow, then the permanent pressure loss caused by orifice meter is given by (ΔP`` - ΔP`).

The relative pressure loss coefficient C_L, is the value of the pressure loss (ΔP`` - ΔP`) relative to the pressure differential indicated by the flow meter ΔP and is given by,

$$C_L = \frac{(\Delta P'' - \Delta P')}{\Delta P}$$

The relative pressure loss C_L for an orifice plate mentioned as per ISO-5167 as,

$$C_L = \frac{\sqrt{1-\beta^4} - C_d\beta^2}{\sqrt{1-\beta^4} + C_d\beta^2}$$

2 LITERATURE SURVEY

Several researchers have investigated the variation co-efficient of discharge of orifice meter for nonstandard conditions for various Reynolds numbers. The following publications related to the topic are utilized to present thesis.

SANGANI et.al [1] had made the attempt to compare the pressure drop across the sharp edged orifice between the experimental values with the theoretical and numerical values. The experiments are conducted in the orifice meter setup and for different flow rates of water and the corresponding pressure drop is calculated based on the orifice meter geometry and inlet velocity, theoretical pressure drop is calculated for different flow rates. The same problem is simulated using ANSYS CFX 15.0 for corresponding flow rates using k-ω model. Results are compared with experimental and theoretical values and it is found that the agreement is reasonably good.

KARTHIK et al [2] have made an attempt to predict the variation of discharge co efficient C_d for nonstandard conditions of plate thickness and pipe diameter. Here they have calculated the co efficient of discharge C_d for standard conditions which are suggested by ISO-5167 and simulated the same problem in ANSYS and verified the result. Then they simulated for nonstandard conditions for the plate thickness of 1mm to 15 mm, pipe diameter of 10mm to

50mm β=0.5 for the Reynolds number of 200 (laminar regime) and 100000 (turbulent regime). The validation of this problem is done by comparing the numerical results with ISO-5167 and BS-1042 standards. First they verified the computational simulation for the standard values of 50mm pipe diameter, diameter ratio of 0.5 for the Reynolds number of 100000 with velocity of 2m/s and 0 gauge pressure at the outlet. The most important thing is selecting the appropriate turbulence model for calculation, and here k-ω SST model gives results which are very near to the standard results. Hence the simulation is done for nonstandard conditions as per ISO-5167 using k-ω SST model and results are tabulated. From this simulation they found that as diameter of the pipe decreases the discharge co-efficient increases gradually.

The maximum allowable plate thickness of the standard orifice plate as per standards for a 50 mm diameter pipe is 3mm and here simulation is done for thickness range from 1 mm to 15 mm for Reynolds number of 200 and 100000 and results are tabulated and it is observed that the discharge co-efficient does not change with the variation of plate thickness up to 5mm hence ISO 5167 correlation can be used to calculate the co-efficient of discharge in 50 mm pipe.

RAMYA et al [3] in their research work made an attempt to predict the performance characteristics of conical entrance orifice operating outside the standard conditions, which are specified in BS-1042.First they simulated the standard problem with ANSYS and compared the result with the values given in BS-1042. Then they simulated the flow for an orifice operating out of standard conditions as follows. They varied the diameter ratio between 0.1 to 0.5 for Reynolds number of 500 and pipe diameter of 100mm. It is observed that in the range of diameter ratios 0.1 to 0.316 the value of discharge coefficient is within the range of 0.7342% as specified by BS 1042. However value of Cd increases monotonically with increasing diameter ratios. At higher diameter ratios beyond 0.316 the value of discharge coefficient increases significantly. Thus, at β=0.5 the value of C_d is 0.8146, which is outside the range specified by BS 1042.Variation of Reynolds number between 1 to 10^6 for pipe diameter of 100 mm, diameter ratio of 0.3 and plate thickness of 7mm, it is observed that for Reynolds number 1 and 10, the values of discharge coefficient are 0.289 and 0.6325 respectively and which are not in the range of 0.7342% as specified by BS 1042. For Reynolds number 50 to 10^6, the values of discharge coefficients are within the range of 0.734 2% as specified by BS 1042.In laminar regime, the coefficient of discharge is increasing monotonically and in turbulent regime the Cd values are increasing marginally with increasing Reynolds number, but the variation is within the specified uncertainty.

Variation of pipe diameter between 10mm to 300mm for Reynolds number of 500 and $5*10^4$ and diameter ratio of 0.3, It is observed that at both Reynolds numbers, in the range of the pipe diameters 10 to 300mm, the values of discharge coefficient are within the range of 0.7342% as specified by BS 1042.However value of Cd marginally decreases with increasing pipe diameters.

MARCELO FILARDI et al [4] conducted the experiments on integral orifice meter to study the influence of roughness factor, eccentricity of orifice hole and geometry of orifice meter on discharge co-efficient. They constructed the experimental setup of orifice for 17mm diameter pipe with corner traps. The integral orifice is manufactured in accordance with the ISA RP 3.2 standards. Measurements are reported over a range of Reynolds numbers for orifice diameters of 3.8, 5.01 and 8.59mm, for three types of orifice plates namely sharp edged, conical entrance and quadrant edge orifice. Further measurements have been made with both concentric and eccentric configurations.

Two pipes are used, one is 20 mm PVC pipe of roughness 0.8 micrometers and second one is 17mm with grooved of 1mm wide and 1mm deep. And they found that for the flow through a square edge eccentric orifice with the smooth pipe the discharge co-efficient, Cd is given by,

$$Cd=\frac{a+cRe\,^\wedge 0.5}{1+bRe\,^\wedge 0.5+dRe}$$

And the values of a, b, c and d are constants and they change for different diameters and they plotted the graph of Re vs Cd for the three types of orifice plates.

MOHAMMAD AZIM AIJAZ et.al [5] have discussed their work "Finite Element Analysis (FEA) of pressure drops in orifice meter". The objective of the project was to compare the theoretical pressure drop and experimental pressure drop. They validated the experimental pressure drop by comparing it with the FEA pressure drop obtained by the CFD code simulations. They calculated theoretically pressure drop for 4 different flow velocities and conducted experiments to find out experimental pressure drop for the same flow velocities. Then they modeled the concentric orifice plate to analyze the FEA pressure drop and compared it with experimental pressure drop. They concluded that average difference between theoretical and experimental pressure drop was 2.2% and the average difference between FEA and experimental pressure drop was 0.9%.

LOW FLOW TRANSMITTER WITH INTEGRAL FLOW ORIFICE BY YOKOGAWA ELECTRIC CORPORATION [6]. In this technical information they have given the technical specifications about the integral orifice meter and differential Pressure transmitter. They mounted the integral orifice plate in line on a nominal 25 mm diameter pipe and they have given the standard specifications for choosing the correct bore diameter for measurement ranges of an equivalent flow of 0.45 to 910 NL/min at zero degree Celsius and 1 atmosphere pressure, water equivalent flow of 0.016 to 33 L/min at 4 degree Celsius and 1 atmosphere pressure. They have also given the plots to choose the bore diameter for different flow rates and Reynolds number, For selecting the suitable bore size and differential pressure range, firstly the 100% flow rate must be converted to equivalent air flow rate at 0°C and 1 atm (if the process fluid is gas) or to the equivalent of water flow rate at 4°C and 1 atm (if the process fluid is a liquid). For conversion they have given set of standard correlations in the tables for dry gases, wet gases and liquids. Then choose the correct bore size using the graphs of differential pressure versus equivalent flow rate for liquids and gases. Then calculate the Reynolds number of the flow and locate the flow coefficient, in the graph of flow Coefficient versus Reynolds number for selected bore diameter. If the point lies outside the curve of constant flow coefficient then there is a correction needed for the calculated differential pressure at the 100% flow rate. If the Reynolds number of the flow lies outside of the band in which flow coefficient is constant, correct the calculated differential pressure at 100% flow rate using the correlations given.

INTEGRAL ORIFICE ASSEMBLY TO MEASURE SMALL FLOW RATES BY HONEYWELL [7]. The manufacturer Honeywell offer six integral orifice plates for ½ inch diameter pipe to measure the flow rate .They manufacture the orifice plates with diameter ranges from 0.0200 inches to 0.3390 inches. And they provided complete installation, maintenance and operational specification.

They conducted the experiments on each orifice plate and they represented them in the form of graphs for both the water flow and air flow. They had given separate graphs of flow rates and differential pressure for liquid as well as gases, for certain range of orifice diameter. One can select the required orifice plate by calculating the equivalent water or air flow rate of fluid. Then use the standard graphs to select the size of orifice and pressure difference range to choose the transmitter.

MEASUREMENT OF FLUID FLOW IN CLOSED CONDUITS BS-1042-1.2 [8]. This is the standard information available in which the standard geometry and flow conditions are mentioned for different types of orifice meters and flow nozzles based on experimental results.

According to this, for a square edged orifice plate with a drain hole, the pipe diameter should be below 100mm, drain hole should not exceed 0.1d, and pressure tapings should be oriented so that they are between 90° and 180° to the position of drain hole.

When a square edge orifice is installed in a pipe line of bore 25mm to 50mm, the corner tappings should be used and

$$Re_D \geq 40000\beta^2 \text{ for } 0.23 \leq \beta \leq 0.5$$
$$Re_D \geq 10000\beta^2 \text{ for } 0.5 \leq \beta \leq 0.7$$

If there is no upstream or downstream pipeline, that is flow from large space in to the pipe or vice versa. In such a case, the upstream pipe is considered large if, there is no wall closer than 4d to the axis of the device, the velocity of the fluid at any point more than 4d from the device is less than 3% of the velocity in the orifice or throat, the diameter of the downstream pipe line should not be less than 2d, the upstream tapping should be located at a distance greater than 5d from the axis of the plate and downstream corner tapping should be used. The space on the downstream side of the orifice is considered to be large, if there is no wall closer than 4d to the axis of plate, the upstream pipe diameter should be greater than 2.5d, upstream corner tapping should be used and downstream tapping should be located at a distance greater than 5d.In same way it has the standard geometrical and flow standards for various types of orifice meters like conical entrance, quarter circle etc.

MEASUREMENT OF FLUID FLOW BY MEANS OF PRESSURE DIFFERENTIAL DEVICES INSERTED IN CIRCULAR CROSS SECTION CONDUITS RUNNING FULL (ISO-5167) [9]. According to ISO-5167, the flow rates through an orifice plate can be calculated without specifically calibrating the individual flow meter so long as the construction and installation of the device complies with the stipulations of the relevant standard or handbook. The calculation takes account of the fluid and fluid conditions, the pipe size, the orifice size and the measured differential pressure; it also takes account of the coefficient of discharge of the orifice plate, which depends upon the orifice type and the positions of the pressure tappings. With local pressure tappings (corner, flange and D & D/2), sharp-edged orifices have coefficients around 0.6 to 0.63, while the coefficients for conical entrance plates are in the range 0.73 to 0.734 and for quarter-circle plates 0.77 to 0.85. The coefficients of sharp-edged orifices vary more with fluids and flow rates than the coefficients of conical-entrance and quarter-circle plates, especially at low flows and high viscosities.

For compressible flows such as flows of gases or steam, an expansibility factor or expansion factor is also calculated. This factor is primarily a function of the ratio of the measured differential pressure to the fluid pressure and so can vary significantly as the flow rate varies, especially at high differential pressures and low static pressures.

The equations provided in American and European national and industry standards and the various coefficients used to differ from each other even to the extent of using different combinations of correction factors. However many are now closely aligned and give identical results; in particular, they use the same Reader-Harris/Gallagher equation for the coefficient of discharge for sharp-edged orifice plates.

3. VALIDATION

The validation is the most important step in any computational analysis of fluid flow. It is the process of comparing the results obtained in the computational analysis with the available standard results.

In this present work, the flow through the standard square edge orifice plate is analyzed and results are compared with the standard values of ISO 5167.

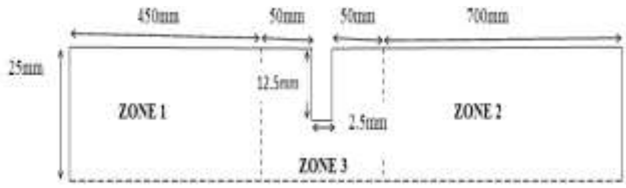

Fig2: GEOMETRY OF THE FLOW DOMAIN

The standard square edge orifice plate geometry is modeled using ANSYS design modeler as shown in Fig2. Since the flow is symmetric about horizontal axis (x-axis), half of the geometry is modeled with the orifice diameter (d) 25mm, pipe diameter (D) 50mm, beta ratio (β) 0.5 and plate thickness (t) 2.5mm. The upstream and down streams are modeled for 10D=500mm and 15D=750mmrespectively.

Incompressible flow of water is considered with the following fluid properties, Reynolds number=5*10^4, free stream velocity=1m/s, density=1000kg/m^3 and viscosity=0.001 Pa-s.

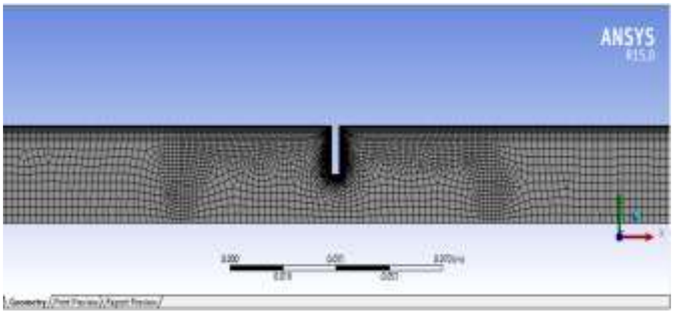

Fig3: MESHING DETAILS

Meshing is done using ANSYS meshing tool. The geometry is divided into three zones as shown in Fig: 2. and zone 1 and zone 2 are meshed using face sizing of 0.5mm, zone 3 is meshed using face size of 0.125mm and inflation is done at the wall boundaries for total thickness of 4mm with 25number of layers and growth rate of 1.2. Hence 374284 number of elements produced with 377311nodes (see Fig.3). The size of the mesh is chosen on the basis of convergence study conducted.

The following boundary conditions are given at different boundaries of the flow domain.

Boundary	Type	Magnitude
Inlet	Velocity-inlet	1 m/s
Outlet	Pressure-outlet	0 Pa (gauge)
Wall	Stationary, No-slip	-----------
Axis	Symmetric	-----------

Table1: BOUNDARY CONDITIONS

The governing equations are solved with SIMPLE algorithm for pressure-velocity coupling, least square cell method for gradient, standard method for pressure, second order upwind scheme for momentum, first order upwind scheme for both turbulence kinetic energy specific dissipation rate and turbulence dissipation rate. In the specification method of k-epsilon with 1% of each for k and epsilon and Specification method of k-omega with 1% of each for k and omega are adopted. The convergence criteria of 10^{-6} is taken for all the parameters. Solutions are obtained for different turbulence models with flange pressure tappings.

By measuring the differential pressure at flange tappings, mass flow rate, density and geometrical parameters of orifice meter, the computational discharge co-efficient and permanent pressure loss co-efficient are calculated for different turbulence models and compared with ISO 5167 standard results and based on the results best turbulence model is selected.

Turbulence model	ΔP in Pa	$(C_d)_{ISO}$	$(C_d)_{CFD}$	% deviation in C_d	$(C_L)_{ISO}$	$(C_L)_{CFD}$	% deviation in C_L
K-ε standard	16458.61	0.6101	0.6750	10.63	0.7278	0.7365	1.19
K-ω standard	19678.55	0.6101	0.6173	1.18	0.7278	0.7358	1.09
K-ω SST	20135.22	0.6101	0.6103	0.03	0.7278	0.7311	0.45

Table 2: CHOICE OF TURBULENCE MODEL

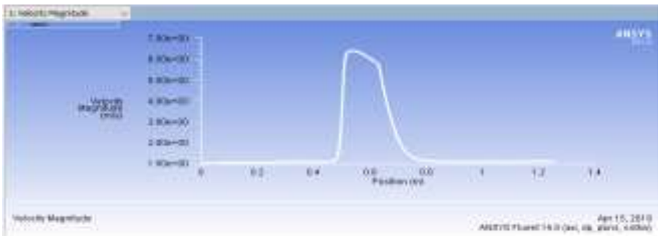

Fig4 (a): VELOCITY PLOT ALONG THEAXIS OF THE PIPE

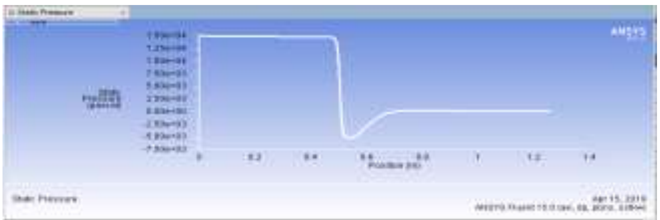

Fig4 (b): VARIATION STATIC PRESSUE ALONG THE PIPE AXIS

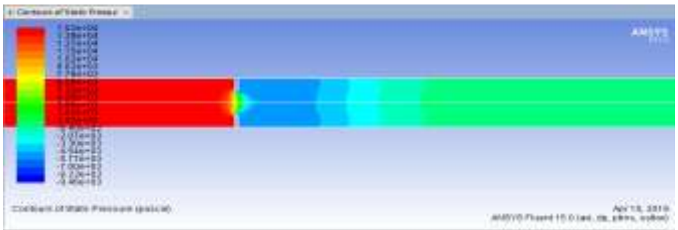

Fig4 (c): PRESSURE CONTOURS

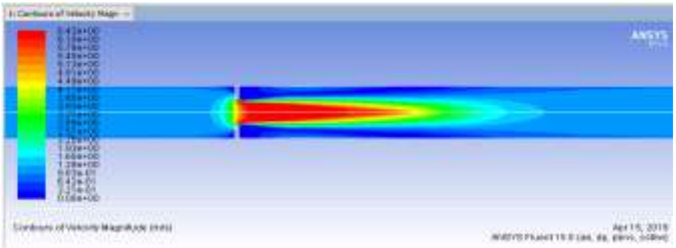

Fig4 (d): VELOCITY CONTOURS

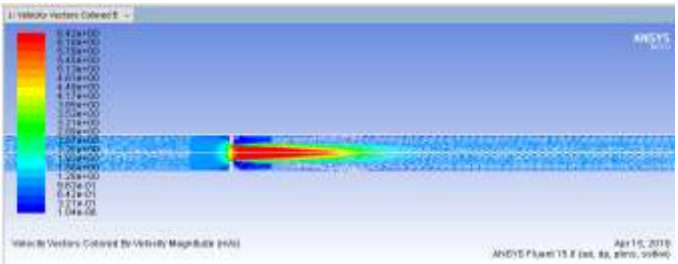

Fig4 (e): VELOCITY VECTOR PLOT

Figs.4 (a to e) show the variation of various flow properties along the length of the pipe. The various details of the flow like sudden changes in pressure and velocity across the orifice plate, pressure recovery after the orifice, recirculation regions etc. are clearly seen from these plots.

From the Table 2, it is noted that the k-ω SST model gives the results which agree with the standard results given in ISO 5167. Hence k-ω SST turbulence model is selected for further analysis of the flow through an orifice meter.

4. ANALYSIS OF FLOW THROUGH INTEGRAL ORIFICE PLATES

In this part of study the incompressible flow through integral orifice plate assemblies is simulated or analyzed and results are compared with the experimental results reported in the literature. For this purpose, the experimental data reported in "Experimental Flow Measurement with Integral Orifice" by Marcelo Filardi et al [5] as well the data given by "Yokogawa Electronics Corporation" [9] in their website are used for the validation of the methodology.

4.1 COMPARISON WITH DATA GIVEN BY "EXPERIMENTAL FLOW MEASUREMENT INTEGRAL ORIFICE" BY MARCELO FILARDI ET AL[4].

The square edge integral orifice plate geometry is modeled using ANSYS design modeler. Since the flow is symmetric about horizontal axis (x-axis), half of the geometry is modeled with the orifice diameter (d) 3.8mm, pipe diameter (D) 17mm, beta ratio (β) 0.223 and plate thickness (t) 2mm. The upstream and down streams are modeled for 10D=170mm and 15D=255mm respectively.

Incompressible flow is considered with the following fluid properties, free stream velocity=1m/s, density=1000kg/m^3.

Meshing is done using ANSYS meshing tool. The geometry is divided into three zones. The zone 1 and zone 2 are meshed using face sizing of 0.25mm, zone 3 is meshed using face size of 0.007mm and inflation is done at the wall boundaries for total thickness of 3mm with 30number of layers and growth rate of 1.2. Hence 238460 number of elements produced with 240907 nodes.

The following boundary conditions are given at different boundaries of the flow domain,

Boundary	Type	Magnitude
Inlet	Velocity-inlet	1 m/s
Outlet	Pressure-outlet	0 Pa (gauge)
Wall	Stationary, No-slip	----------
Axis	Symmetric	----------

Table3: BOUNDARY CONDITIONS

The governing equations are solved with SIMPLE algorithm for pressure-velocity coupling, least square cell method for gradient, standard method for pressure, second order upwind scheme for momentum, first order upwind scheme for both turbulence kinetic energy specific dissipation rate and turbulence dissipation rate, the value of 1% is specified for k-omega in the k-omega-SST model. The convergence criteria of10^{-6} is taken for all the parameters. Solutions are obtained for different Reynolds numbers and corresponding viscosities with corner pressure tappings. These are exactly identical settings arrived at the validation studies. Various Reynolds numbers are achieved by properly specifying the viscosity while keeping the other flow parameters same.

By measuring the differential pressure at corner tappings, mass flow rate, density and geometrical parameters of orifice meter, the computational discharge co-efficient and permanent pressure loss co-efficient are calculated for different Reynolds numbers and corresponding viscosities and compared with experimental results.

Re	ΔP in Pa	$(C_d)_{CFD}$	$(C_d)_{EXP}$	% deviation in C_d	C_L
1000	311285	0.7980	0.7789	2.45	0.9304
3000	475706.2	0.6455	0.6276	2.85	0.9386
5000	476500.7	0.6450	0.6153	4.60	0.9390

Table4: COMPARISON BETWEEN EXPERIMENTAL AND COMPUTATIONAL RESULTS FOR SQUARE EDGE ORIFICE (β= 0.223, D= 17mm)

Re	ΔP in Pa	$(C_d)_{CFD}$	$(C_d)_{EXP}$	% deviation in C_d	C_L
3000	266841.1	0.8619	0.8102	6.38	0.9160
5000	264155.1	0.8663	0.7882	9.90	0.9160
7000	262665.3	0.8687	0.7823	11.00	0.9161

Table5: COMPARISON BETWEEN EXPERIMENTAL AND COMPUTATIONAL RESULTS FOR CONICAL ENTRANCE ORIFICE (β= 0.223, D= 17mm)

Re	ΔP in Pa	$(C_d)_{CFD}$	$(C_d)_{EXP}$	% deviation in C_d	C_L
3000	245952.8	0.8978	0.9529	-5.78	0.9110
5000	243783.4	0.9018	0.9352	-3.57	0.9109
7000	242980.8	0.9032	0.9323	-3.12	0.9110

Table6: COMPARISON BETWEEN EXPERIMENTAL AND COMPUTATIONAL RESULTS FOR QUARTER CIRCLE ORIFICE (β= 0.223, D= 17mm)

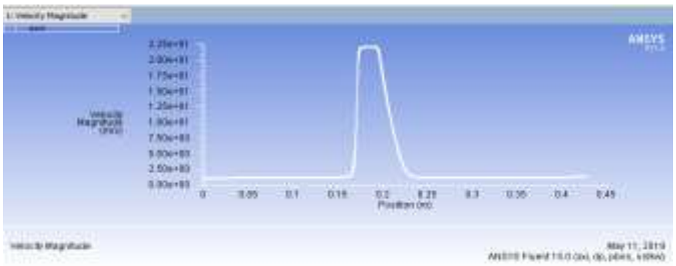

Fig5 (a): VELOCITY PROFILE ALONG THE AXIS OF PIPE

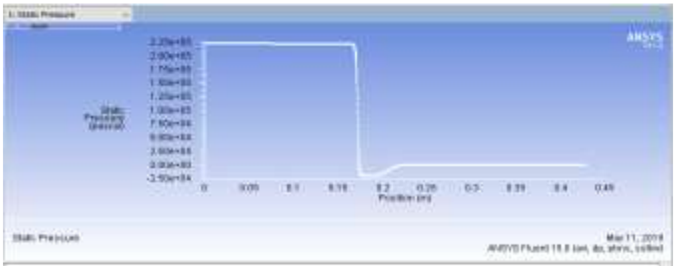

Fig5 (b): PRESSURE PROFILE ALONG THE AXIS OF PIPE

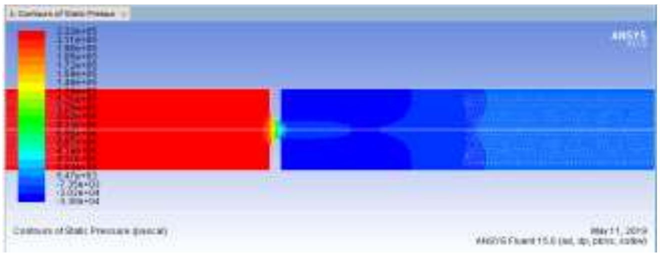

Fig5(c): PRESSURE CONTOURS

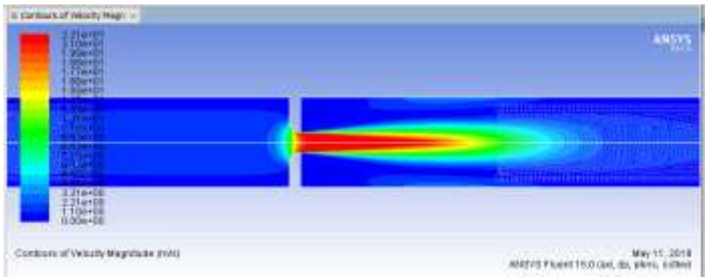

Fig5 (d): VELOCITY CONTOURS

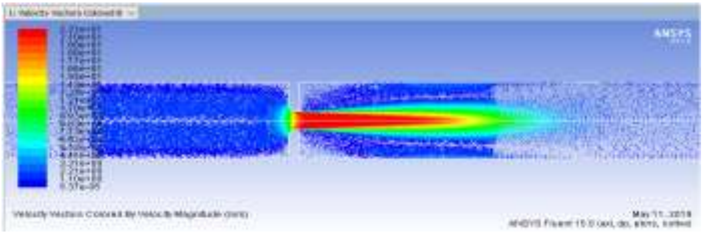

Fig5 (e): VELOCITY VECTOR PLOT

Figs.5 (a to e) show the variation of various flow properties along the length of the pipe. The various details of the flow like sudden changes in pressure and velocity across the orifice plate, pressure recovery after the orifice, recirculation regions etc. are clearly seen from these plots.

From the Table4 it is noted that the permanent pressure loss co-efficient for square edge integral orifice remains constant and it is almost equal to 0.93. It indicates that there is no appreciable pressure recovery in the square edge integral orifice plate assemblies at lower Reynolds numbers. These values are much higher as compared to standard orifice plates. Further, it is observed that the Computed values of C_d decrease with increasing Reynolds numbers which is in agreement with experimental data. The computed values of C_d at any Reynolds no. are somewhat higher than the experimentally measured values. However the reported uncertainty in the measurements are of the order ±5%. In addition, Marcello Filardi et.al have not specified all the details like plate thickness, provision of chamfering, edge finish etc. In view of this, the agreement can be considered as reasonable.

From Table5 it is noted that the permanent pressure loss co-efficient remains constant and it is almost equal to 0.916. It indicates that there is no appreciable pressure recovery in the conical entrance integral orifice plate assemblies at lower Reynolds numbers. And it is observed that as compared to square edge orifice assemblies, the pressure recovery is slightly higher in conical edge orifice assemblies.

From the Table6 it is noted that the permanent pressure loss co-efficient is remains constant and its almost equal to 0.91. It indicates that there is no appreciable pressure recovery in the quarter circle integral orifice plate assemblies at lower Reynolds number. And also it is observed that, the pressure recovery through quarter circle orifices is slightly higher than square edge orifices and comparably same as conical entrance orifices.

From the comparison of computational values of co-efficient of discharge for range of Reynolds number for flow through various types of namely, square edge, conical entrance and quarter circle integral orifice plate assemblies. It is observed that the computational results are close to experimental results with errors, within the expected uncertainty limits. The causes of deviations can be attributed to experimental errors and lack of detailed data on all the geometric parameters. Hence it is concluded that the experimental results are acceptable within the range of error and CFD methodology can be used as a tool to analyze the flow through any integral orifice plate assemblies.

4.2 COMPARISON WITH EXPERIMENTAL RESULTS GIVEN BY YOKOGAWA ELECTRONIC CORPORATION[6]

In this present work CFD analysis of incompressible flow through the square edge integral orifice plate assemblies is carried out for different flow rates and diameter ratios and Computational results are validated with the technical data given by the Yokogawa electronic corporation. The analysis is carried out for the bore diameters of 1.51mm, 2.527mm and4.04mm for different flow rates within the limit given by the manufacture.

The square edge integral orifice plate geometry is modeled using ANSYS design modeler. Since the flow is symmetric about horizontal axis (x-axis), half of the geometry is modeled with the orifice diameter (d) 4.04mm, pipe diameter (D) 17mm, beta ratio (β) 0.2377 and plate thickness (t) 3mm and the upstream edge is rounded with a radius of curvature of 0.1mm. The upstream and down streams are modeled for 10D=170mm and 15D=255mm respectively. Incompressible flow is considered with fluid density=1000kg/m^3, viscosity=0.001Pa-sec and the different flow rates are chosen within the limit given by manufactures. Other fluid properties are considered according to geometrical properties and know fluid properties.

Here also the same computational methodology and boundary conditions used for analysis of flow through integral orifices are used.

Q in lit/min	ΔP in Pa	$(C_d)_{CFD}$	$(C_d)_{STD}$	% deviation in C_d
4.7	20516.15	0.9529	0.9537	-0.08
6.3	50235.77	0.8162	0.8530	-4.31

Table7: VALIDATION OF RESULTS WITH STANDARD RESULTS FOR d=4.04mm

Q in lit/min	ΔP in Pa	$(C_d)_{CFD}$	$(C_d)_{STD}$	% deviation in C_d
2	26760.78	0.9087	0.8582	5.88
3	62968.74	0.8886	0.8488	4.68

Table8: VALIDATION OF RESULTS WITH STANDARD RESULTS FOR d=2.527mm

Q in lit/min	ΔP in Pa	$(C_d)_{CFD}$	$(C_d)_{STD}$	% deviation in C_d
1.5	133246.36	0.8670	0.8819	-1.68
2	235119.61	0.8587	0.8778	-2.17

Table9: VALIDATION OF RESULTS WITH STANDARD RESULTS FOR d=1.51mm

From Tables 7,8,9 it is noted that the computational results are in close agreement with the results given by the Yokogawa Electronic Corporation with the deviations being within the acceptable limit. Hence it can be concluded that, the computational procedure followed for the flow analysis can be used for further analysis of flows through any other integral orifice plate assemblies.

And also the value of discharge co-efficient is slightly higher in case of upstream rounded square edge orifices compared to sharp edge orifices.

5 PARAMETRIC STUDIES

In this section, CFD analysis is carried out on different types of integral orifice plate assemblies namely, square edge, conical entrance and quarter circle integral orifice plate assemblies for wide range of Reynolds number and diameter ratio. The geometry, meshing and boundary conditions are considered as same as considered for "**ANALYSIS OF FLOW THROUGH INTEGRAL ORIFICE PLATES"** for different values of Reynolds numbers and diameter ratio and corresponding viscosities of liquid.

5.1 EFFECT OF REYNOLDS NUMBER ON CHARACTERISTICS OF SQUARE EDGE INTEGRAL ORIFICE PLATE ASSEMBLIES

For square edge integral orifice plate geometry, meshing, boundary conditions and solutions are considered as it is considered for "**ANALYSIS OF FLOW THROUGH INTEGRAL ORIFICE PLATES"**. Reynolds number is varied from 10^4 to 10^5 for square edge, and 10^4 to 5×10^5 for conical entrance and quarter circle orifices and corresponding viscosities are considered for the analysis. Here the CFD analysis is carried out to validate the empirical relationship given for discharge co-efficient of square edge integral orifice plate assemblies and corresponding values of permanent pressure loss co-efficient are calculated and tabulated.

And for conical entrance and quarter circle orifices variation of discharge co-efficient and permanent pressure loss co-efficient with Reynolds number are studied.

According to the experimental work carried by **MARCELO FILARDIet.al** for the square edge integral orifice plates the discharge co-efficient is given by the following relationship,

$$Cd=\frac{a+cRe^{0.5}}{1+bRe^{0.5}+dRe}$$

Where
a=0.501194
b=-0.041487
c=-0.023034
d=2.02628×10^{-5}

Re	ΔP in Pa	$(C_d)_{STD}$	$(C_d)_{CFD}$	% deviation in C_d	C_L
10000	477448.2	0.6117	0.6443	5.32	0.9396
15000	478134.7	0.6141	0.6439	4.85	0.9398
20000	478625.1	0.6177	0.6436	4.19	0.9399
50000	480032.5	0.6400	0.6426	0.40	0.9403
75000	480627.2	0.6567	0.6422	-2.20	0.9404
100000	481169.1	0.6720	0.6418	-4.49	0.9406

Table10: COMPARISON BETWEEN EXPERIMENTAL AND COMPUTATIONAL RESULTS FOR SQUARE EDGE ORIFICE. (β= 0.223, D= 17mm)

Re	ΔP in Pa	$(C_d)_{CFD}$	C_L
10000	261478.5	0.8707	0.9162
15000	260460.2	0.8724	0.9162
20000	259907.8	0.8733	0.9163
25000	259561.9	0.8739	0.9163
50000	258719	0.8753	0.9163

Table11: COMPUTATIONAL RESULTS FOR CONICAL ENTRANCE ORIFICE. (β= 0.223, D= 17mm)

Re	ΔP in Pa	$(C_d)_{CFD}$	C_L
10000	242448.9	0.9042	0.9111
15000	242017	0.9050	0.9113
20000	241762.7	0.9055	0.9851
25000	241593.4	0.9058	0.9844
50000	241134.9	0.9067	0.9831

Table12: COMPUTATIONAL RESULTS FOR QUARTER CIRCLE ORIFICE. (β= 0.223, D= 17mm)

From the Table10, it is observed that, the computational values of discharge co-efficient is constant above the Reynolds number 3000 and the discharge co-efficient calculated by the empirical formulae increases as Reynolds number increase. From Table10 it is noted that the empirical formulae is no longer valid at higher Reynolds number.

From Table10 it is noted that the co-efficient of permanent pressure loss is around 0.93 up to Reynolds number of 20000 and it increases slightly at higher Reynolds number hence at higher Reynolds numbers pressure loss is higher. From Tables (11, 12) it is noted that at higher Reynolds numbers the discharge co-efficient for conical entrance and quarter circle integral orifice plate assemblies remains constant and its equals to around 0.87 for conical entrance and 0.9 for quarter circle orifices. And also its observed that the permanent pressure loss co-efficient is constant at all Reynolds number for conical entrance orifice and its equal to around 0.91. And for quarter circle orifices the pressure loss co-efficient increases at higher Reynolds numbers as happens in case of square edge orifices.

5.2 EFFECT OF DIAMETER RATIO ON CHARACTERISTICS OF INTEGRAL ORIFICE PLATE ASSEMBLIES

The diameter ratio plays an important role in characteristics of integral orifice plate assemblies. In this part of study, CFD analysis is carried out for different type of integral orifice plate assemblies namely, square edge, conical entrance and quarter circle orifice plate assemblies for a diameter ratio of 0.2947 For Reynolds number varying from 3000 to 40000 and corresponding viscosities. And the discharge co-efficient for range of Reynolds number are calculated by using computed differential pressure and other geometrical parameters and corresponding values of permanent pressure loss co-efficient are calculated and tabulated.

Re	ΔP in Pa	$(C_d)_{CFD}$	C_L
3000	266841.1	0.4946	0.9160
5000	264155.1	0.4971	0.9160
10000	261478.5	0.4996	0.9162
20000	259907.8	0.5011	0.9163
30000	259313.6	0.5017	0.9163
40000	258963.2	0.5020	0.9163

Table13: VARIATION OF DISCHARGE CO-EFFICIENT WITH REYNOLDS NUMBER FOR SQUARE EDGE INTEGRAL ORIFICE WITH d=5.01mm

Re	ΔP in Pa	$(C_d)_{CFD}$	C_L
3000	160250.8	0.6382	0.8935
5000	161211.4	0.6363	0.8945
10000	162205.2	0.6344	0.8956
20000	162642.2	0.6335	0.8963
30000	163159.7	0.6325	0.8967
40000	164941.3	0.6291	0.8971

Table14: VARIATION OF DISCHARGE CO-EFFICIENT WITH REYNOLDS NUMBER FOR CONICAL ENTRANCE INTEGRAL ORIFICE WITH d=5.01mm

Re	ΔP in Pa	$(C_d)_{CFD}$	C_L
3000	83678.7	0.8832	0.8523
5000	82987	0.8869	0.8522
10000	82299	0.8906	0.8522
20000	81964.5	0.8924	0.8524
30000	81857.2	0.8930	0.8524
40000	81799.9	0.8933	0.8523

Table15: VARIATION OF DISCHARGE CO-EFFICIENT WITH REYNOLDS NUMBER FOR QUARTER CIRCLE INTEGRAL ORIFICE WITH d=5.01mm

From the tables (13, 14. 15) it is noted that for bore diameter 5.01mm the discharge co-efficient remains constant over a Reynolds number range of 10000 to 50000. And it is equal to 0.5 for square edge, 0.63 for conical entrance and 0.89 for quarter circle orifices.

It is also noted that, for all types of orifices the discharge co-efficient reduces as diameter increases. And also its noted that, as the bore diameter increases the permanent pressure loss co-efficient reduces. That means as diameter increases, the pressure recovery also increases.

6 ANALYSIS OF FLOW THROUGH ORIFICES IN THE ABSENCE OF UPSTREAM AND DOWNSTREAM PIPELINES

In this case study we are interested in how the co-efficient of discharge varies with absence of upstream and downstream pipelines. When there is no wall within the distance 4d from the axis or plane of the orifice plate, it is considered as no upstream and downstream effect or pipelines. CFD analysis of the flow through the standard orifice plate with no upstream and downstream pipeline effect is carried out and results are validated with BS 1042 standards, then the variation of Reynolds number and bore diameter are varied out of range of standards to study the variation of co-efficient of discharge.

For the flow through the standard orifice assemblies with no upstream and downstream effect the following conditions has to be satisfied.

d>6mm

β≤0.125 for both upstream and downstream

D≥8d

R_{ed}>50000

C_d=0.596

6.1 CFD ANALYSIS OF FLOW THROUGH STANDARD SQUARE EDGE ORIFICE WITH NO UPSTREAM AND DOWNSTREAM EFFECT

The square edge integral orifice plate with no upstream and downstream effect is modeled by using ANSYS design modeler. Since the flow is symmetric about horizontal axis (x-axis), half of the geometry is modeled with the orifice diameter (d) 6mm, pipe diameter (D) 48mm, beta ratio (β) 0.125 and plate thickness (t) 3mm. The upstream and down streams are modeled for 10D=480mm and 15D=720mm respectively. And the downstream of the orifice plate is chamfered for 1mm with chamfering angle of 45 degrees. Incompressible flow is considered with the following fluid properties, free stream velocity=0.15625m/s and density=1000kg/m^3.

Meshing, boundary conditions and solution methods are considered as same as considered for "**ANALYSIS OF FLOW THROUGH INTEGRAL ORIFICE PLATES"** for different values of Reynolds numbers and corresponding viscosities of liquid.

R_{ed}	ΔP in Pa	$(C_d)_{CFD}$
10000	126630.27	0.6282
30000	127785.7	0.6258
100000	128518.9	0.6236

Table16: VARIATION OF DISCHARGE CO-EFFICIENT WITH REYNOLDS NUMBER FOR STANDARD SQUARE EDGE ORIFICE (β= 0.125, D= 48mm)

From the Table17 it is noted that at Reynolds number 100000, the computational discharge co-efficient is 0.6236. According to BS 1042, if all the standard conditions are satisfied, the value of discharge co-efficient is 0.596 which is constant over a Reynolds number above 50000. And the computational result shows that the values remain constant, even if Reynolds number is below 50,000 with uncertainty of 4.63%, which is within the acceptable limit.

Hence it is concluded that, the discharge co-efficient for a square edge standard orifices with no upstream and downstream pipeline effect, will remain constant over all range of Reynolds number. And also CFD methodology followed for the analysis can be adopted for analysis of flow through integral orifices too.

6.2 CFD ANALYSIS OF FLOW THROUGH INTEGRAL ORIFICE PLATE ASSEMBLIES WITH NO UPSTREAM AND DOWNSTREAM EFFECT

In this present work CFD analysis of flow of incompressible fluid is carried out for different type of integral orifice plate assemblies namely, square edge, conical entrance and quarter circle integral orifice plate assemblies for range of Reynolds number and the variation of discharge coefficient is calculated by using computed pressure drop across the orifice plates and other geometrical parameters.

The geometries of integral orifice plate assemblies with no upstream and downstream effect are modeled using ANSYS design modeler. Since the flow is symmetric about horizontal axis (x-axis) for all types of orifice assemblies hence half of the geometries are modeled with the orifice diameter (d) 4mm, pipe diameter (D) 32mm, beta ratio (β) 0.125, and plate thickness (t) 3mm.The upstream and down streams are modeled for 10D=320mm and 15D=480mm respectively.

Incompressible flow is considered with the following fluid properties, free stream velocity=1.25m/s, density=1000kg/m^3 and corresponding viscosities are considered according to the values of Reynolds number.

Meshing, boundary conditions and solution methods are considered as same as considered for "**ANALYSIS OF FLOW THROUGH INTEGRAL ORIFICE PLATES**" for different values of Reynolds numbers and corresponding viscosities of liquid.

R_{ed}	ΔP in Pa	$(C_d)_{CFD}$
10000	6927400	0.6795
30000	6936274	0.6791
100000	7020824	0.6750

Table17: VARIATION OF DISCHARGE CO-EFFICIENT WITH REYNOLDS NUMBER FOR SQUARE EDGE INTEGRAL ORIFICE (β= 0.125, D= 32mm)

R_{ed}	ΔP in Pa	$(C_d)_{CFD}$
10000	4358219	0.8567
30000	4391867	0.8534
100000	4358219	0.8567

Table18: VARIATION OF DISCHARGE CO-EFFICIENT WITH REYNOLDS NUMBER FOR CONICAL ENTRANCE INTEGRAL ORIFICE (β= 0.125, D= 32mm)

R_{ed}	ΔP in Pa	$(C_d)_{CFD}$
10000	3900312	0.9056
30000	3801829	0.9173
100000	3751991	0.9234

Table19: VARIATION OF DISCHARGE CO-EFFICIENT WITH REYNOLDS NUMBER FOR QUARTER CIRCLE INTEGRAL ORIFICE (β= 0.125, D= 32mm)

From the Table17 it is noted that, for bore diameter less than 6mm, particularly for 4mm the discharge co-efficient increase slightly and its equal to around 0.67 for square edge integral orifices. And also it remains constant over a range of Reynolds number from 10000 to 100000.

The discharge co-efficient for conical entrance and quarter circle integral orifices with no upstream and downstream pipelines effect are slightly high compare to square edge orifices and they are equal to 0.85 and 0.91 respectively.

Hence it is concluded that, for all type of orifices with no upstream and downstream pipelines effect, the discharge co-efficient is independent of Reynolds number and in increases as bore diameter reduces.

7 COMPRESSIBLE FLOW ANALYSIS THROUGH ORIFICE PLATE ASSEBLIES

In this present work the compressible flow through the standard orifice plate assemblies is analyzed by using CFD technique and the computational expansion factor is calculated and compared with the standard expansion factor given by ISO 5167 and BS 1042 norms. And the compressible flow through the various types of integral orifice plate assemblies are analyzed for different values of Reynolds numbers and corresponding expansion factors are calculated and tabulated.

7.1 COMPRESSIBLE FLOW THROUGH THE STANDARD SQUARE EDGE ORIFICE PLATE

In this section the compressible flow of air through the standard square edge orifice plate is analyzed and results are validated with ISO5167 and BS1042 norms.

The standard square edge orifice plate geometry is modeled using ANSYS design modeler as modeled in "**FLOW THROUGH STANDARD SQUARE EDGE ORIFICE PLATE ASSEMBLIES**" Since the flow is symmetric about horizontal axis (x-axis), half of the geometry is modeled with the orifice diameter (d) 25mm, pipe diameter (D) 50mm, beta ratio (β) 0.5 and plate thickness (t) 2.5mm. The upstream and down streams are modeled for 10D=500mm and 15D=750mm respectively.

The compressible flow of air is considered with the following fluid properties, Reynolds number 5*10^4, free stream velocity 6 m/s, density at the inlet 1.225 kg/m^3 and viscosity 7.35×10^{-6}Pa-s and air is assumed as ideal gas.

Meshing is done using ANSYS meshing tool. The geometry is divided into three zones as shown in Fig: 3.1 and zone 1 and zone 2 are meshed using face sizing of 0.5mm, zone 3 is meshed using face size of 0.125mm and inflation is done at the wall boundaries for total thickness of 4mm with 25number of layers and growth rate of 1.2. Hence 374284 number of elements produced with 377311nodes.

The following momentum and thermal boundary conditions are applied at different boundaries of flow domain.

Boundary	Type	Magnitude

Inlet	Velocity-inlet	6m/s
Outlet	Pressure-outlet	0 Pa (gauge)
Wall	Stationary, No-slip	-----------
Axis	Symmetric	-----------

Table20: MOMENTUM BOUNDARY CONDITIONS

Boundary	**Type**	Magnitude
Inlet	Temperature	300K
Outlet	Back flow total temperature	300K
Wall	Heat flux Heat generation rate	0w/m^2 0w/m^3

Table21: THERMAL BOUNDARY CONDITIONS

The Spalart-Allmaras (1 equation)turbulence model is adopted for analysis of compressible flow with pressure based solver and The governing equations are solved with simple algorithm for pressure-velocity coupling, least square cell method for gradient, standard method for pressure, second order upwind scheme for momentum and pressure and first order upwind scheme for modified turbulence viscosity. The convergence criteria of 10^{-6} is taken for all the parameters and the differential pressure drop is measured by using a flange pressure tappings.

By using the differential pressure, mass flow rate, density and geometrical parameters, the computational discharge coefficient for compressible flow is calculated. And using the computational co-efficient of discharge for incompressible flow, the computational expansion factor is calculated and validated with the ISO 5167 and BS 1042 norms.

Re	ΔP in Pa	C_{dc}	C_{di}	ε_{cfd}	ε_{iso}	% deviation in ε
50000	1016.16	0.5705	0.6103	0.9347	0.9470	1.32

Table22: COMPARISON BETWEEN COMPUTATIONAL AND STANDARD RESULTS

From the Table22 it is observed that the computational value of expansion factor agrees closely to the value given by ISO 5167 with uncertainty of 1.32%, which is in the acceptable range. Hence it is concluded that the same computational methodology can be adopted for the analysis of compressible flows through the integral orifice assemblies.

7.2 COMPRESSIBLE FLOW THROUGH THE INTEGRAL ORIFICE PLATE ASSEMBLIES

In this part of study CFD analysis of compressible flow through different types of integral orifice assemblies is carried out for range of Reynolds number and by using results of incompressible flow, the corresponding values of expansion factors are calculated and tabulated.

The geometry of a flow domain is constructed by using an ANSYS design modeler and the meshing and all the geometrical parameters are considered as same as taken for different types of integral orifice plate assemblies in the section **"FLOW THROUGH INTEGRAL ORIFICE PLATE ASSEMBLIES"**.

The boundary conditions and solution methods are applied at different boundaries of flow domain as same as applied for compressible flow through standard orifices with inlet velocity of 5m/s.

Re	ΔP in Pa	C_{dc}	C_{di}	ε_{cfd}
1000	18510.02	0.5749	0.6378	0.9015
3000	16982.51	0.6001	0.6455	0.9296
5000	15253.63	0.6332	0.6450	0.9817

Table22: VARIATION OF EXPANSION FACTOR WITH REYNOLDS NUMBER FOR SQUARE EDGE INTEGRAL ORIFICE PLATE ASSEMBLY

Re	ΔP in Pa	C_{dc}	C_{di}	ε_{cfd}
3000	9186.72	0.8160	0.8619	0.9467
5000	8796.45	0.8339	0.8663	0.9625
7000	8738.93	0.8367	0.8687	0.9631

Table24: VARIATION OF EXPANSION FACTOR WITH REYNOLDS NUMBER FOR CONICAL ENTRANCE INTEGRAL ORIFICE PLATE ASSEMBLY

Re	ΔP in Pa	C_{dc}	C_{di}	ε_{cfd}
3000	8302.19	0.8584	0.8978	0.9561
5000	8284.57	0.8593	0.9018	0.9528
7000	8287.11	0.8592	0.9032	0.9513

Table25: VARIATION OF EXPANSION FACTOR WITH REYNOLDS NUMBER FOR QUARTER CIRCLE INTEGRAL ORIFICE PLATE ASSEMBLY

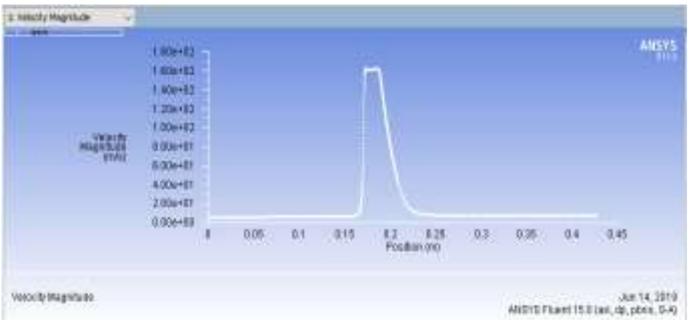

Fig6 (a): VELOCITY PLOT ALONG THE AXIS OF THE PIPE

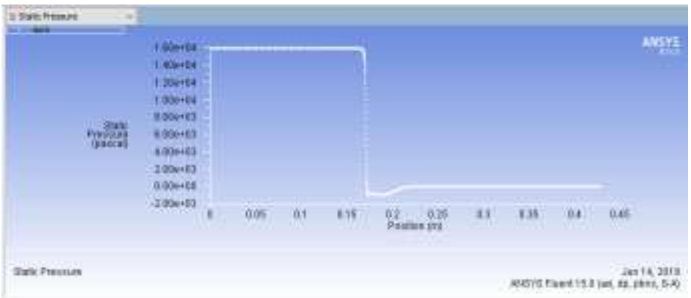

Fig6 (b): VARIATION OF STATIC PRESSURE ALONG THE PIPE AXIS

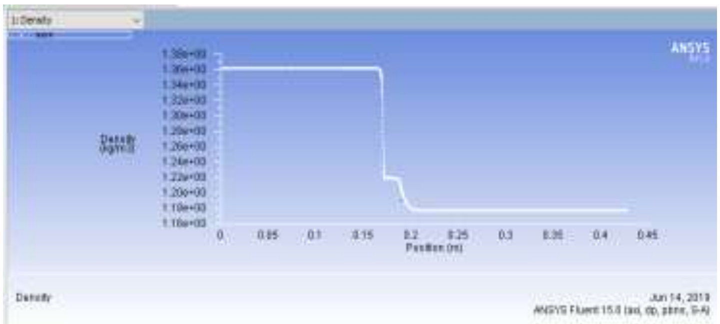

Fig6 (c): VARIATION OF DENSITY ALONG THE PIPE AXIS

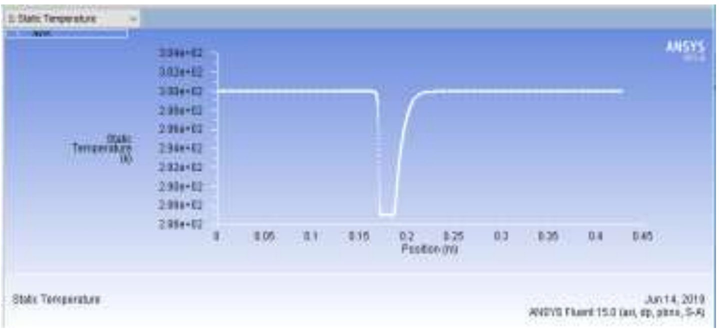

Fig6 (d): VARIATION OF TEMPERATURE ALONG THE PIPE AXIS

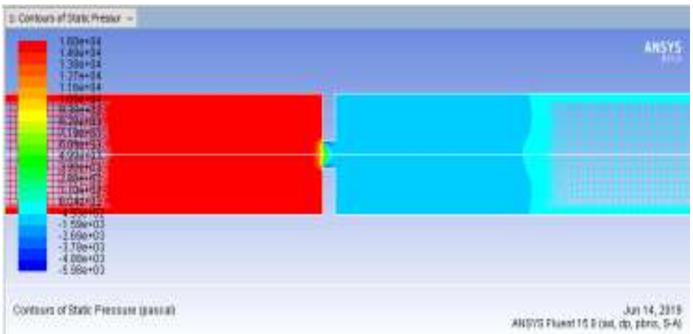

Fig6 (e): PRESSURE CONTOURS

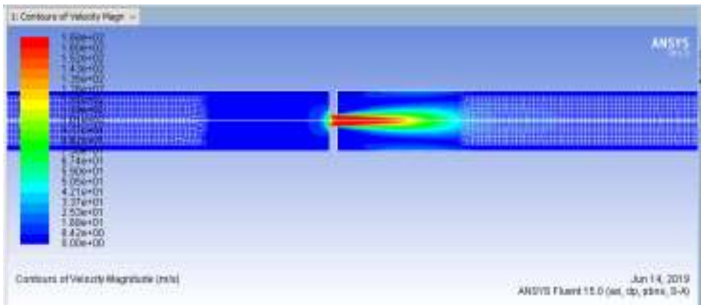

Fig6 (f): VELOCITY CONTOURS

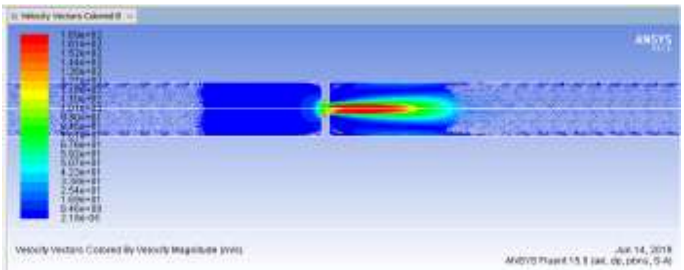

Fig6 (g): VELOCITY VECTOR PLOT

Figs6 (a to g) show the variation of various flow properties along the length of the pipe. The various details of the flow like sudden changes in pressure and velocity across the orifice plate, pressure recovery after the orifice, recirculation regions etc. are clearly seen from these plots.

From the Fig6 (e) it is observed that, the maximum pressure is observed at the region where flow approaches the orifice. And it keeps on reduces as passes through plate. It reaches minimum slightly lower in the downstream and starts to recover afterwards but does not reaches to upstream pressure.

From velocity contours (Fig6 (f)) it is noted that the maximum velocity comes out as jet at the center line from the plate hole and its reaches downstream up to 1D.

From Fig6 (g) the separated regions can be clearly seen. The separated region extends up to 1D in the downstream.

Figs(6(c), 6(d)) shows the variation of density and temperature along the axis of the pipeline. It is observed that there is a reduction in the both density and temperature as flow passes through orifice and temperature starts to recover to upstream value as flow goes to downstream.

From Tables (23, 24, 25) it is noted that, the discharge co-efficient for compressible flow is always less than incompressible flow for all types of integral orifices. The expansion factor for conical entrance and quarter circle orifices is around 0.95and it remains constant at lower turbulent flows. For square edge orifice the expansion factor is around 0.98 at turbulent flow regime and it is slightly high compare to other types of orifices. And as flow becomes laminar expansion factor reduces considerably.

8 CONCLUDING REMARKS

A CFD methodology for analysis of flow through integral orifice plates has been presented. This computation methodology has been validated by comparing results for a standard square edge orifice plate.

Further analysis is carried out for integral orifices working under diverse working conditions like outside the standard Reynolds number diameter ratio and no upstream and downstream pipeline effects,

And also compressible flow through standard square edge orifice is validated by using standard results given by BS 1047 and same computational methodology is used for further analysis of compressible flow through integral orifices and variation of expansion factor with Reynolds number has been studied.

REFERENCES

1. C. R. Sanghani, D. C. Jayani, A. H. Hingu, M. Y. Jadav, D. V. Jiyavia "Comparison of Experimental, Theoretical and Simulation result for Pressure Drop in Sharp Edged Orifice meter". International Journal of Science, Engineering and Technology Research (IJSETR), Volume 5, Issue 3, March 2016.

2. Karthik G S, Yogesh Kumar K J, V Seshadri "Prediction of Performance Characteristics of Orifice Plate Assembly for Non-Standard Working Conditions using CFD". International Journal of Engineering and Technical and Research (IJERT).ISSN: 2321-0869, Volume-3, Issue-5, May 2015, pp. 162-167.

3. Ramya B N, Prof. Yogesh Kumar K J, Dr. V Seshadri "Numerical Analysis of the Performance Characteristics of Conical Entrance Orifice Meter". International Journal of Science, Engineering and Technology Research (IJSETR), ISSN: 2277-9655, 4(12): December 2015.

4. Marcelo Filardi, Edson Del Rio Vieira, Sérgio Said Mansur "Experimental Flow Measurement with Integral Orifice"14th Brazilian Congress of Thermal Sciences and Engineering Copyright © 2012 by ABCM November 18-22, 2012, Rio de Janeiro, RJ, Brazil, https://www.gateresearch.net/publication/235760 342.

5. Haikrishna V. Gohil, Mohammad AzimAijaz "Finite Element Analysis of Pressure Drop in Orifice Meter"". International Journal of Science, Engineering and Technology Research (IJSETR), ISSN: 2278-0181, Volume 3, Issue 3, March-2014.

6. Yokogawa "Low Flow Transmitters with Integral Flow Orifice". https://web-material3.yokagawa.com.

7. Honeywell "Integral Orifice Assembly to Measure Small Flow Rates". www.honeywellprocess.com.

8. British Standards Institution, "BS 1042-1.5:1997" Measurement of fluid flow in closed conduits.

9. Bureau of Indian Standards, "IS 14615 (Part 1), ISO 5167-1:1999", Measurement of Fluid Flow by Means of Pressure Differential Devices, New Delhi.